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Flexible Display Technologies . . . Do They Have a Role in the Cockpit? (Reprint)

By Clarence E. Rash, Eric S. Harris, and William H. McGilberry

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13. ABSTRACT *(Maximum 200 words)*
The 21st century promises a new "holy grail" of display technologies. With the long-promised arrival of the plasma display allowing "hang-on-the-wall" television, the display community has moved on to the promise of fully conformable displays, known as flexible displays. This touted new class of displays is not actually unique in itself but is actually an assortment of novel subclasses of existing display technologies. These technologies include liquid crystal, light emitting diode (LED) and electrophoresis. Flexible displays based on these technologies are advertised as thinner (almost paper thin), lighter weight, stronger (extremely rugged and durable), cheaper, super efficient and conformable, as compared to current rigid, mounted displays. Currently, organic LED (OLED) and electrophoretic displays are examples of flexible displays that have entered the commercial market. The aviation community may find these displays highly desirable for cockpit applications. However, care must taken to ensure that good human factors engineering principles are adhered to in such applications.

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Flexible Display Technologies...Do they have a role in the cockpit?

The Aerospace Lighting Institute
Night Vision Goggle (NVG) and Glass Cockpit Lighting Seminar

Clarence E. Rash, Eric S. Harris, and William H. McGilberry
U.S. Army Aeromedical Research Laboratory
Fort Rucker, Alabama

Over the past two decades, the display industry has seen a revolution in display technology hierarchy. The venerable cathode-ray-tube (CRT) has been usurped by a class of display technologies referred to collectively as flat panel displays. The dominating member of this class is the liquid crystal display (LCD), with its never-ending variety of materials and implementations. Other prominent members include light emitting diode (LED) and plasma displays. Additional emerging flat panel display technologies include electroluminescence (EL), electrophoresis (EP), digital micromirror (DM), electrochromism (EC), and field emission.

While the physics of the various flat panel display technologies have been known since the 1950s, the lack of mature manufacturing capabilities hindered displays based on these technologies from moving beyond dreams and expectations into commonplace applications. It was not until the late 1990s that the emergence of flat panel display technologies, primarily LCD and plasma, finally produced the long-promised delivery of thin, flat television screens that can be hung on the wall.

Poised here at the beginning of the 21st century, we find the display industry again promising revolutionary displays. Industry prognosticators tantalize user communities with computer displays that can be rolled up into a pen (Figure 1), multimedia presentation displays that follow the contours of curved walls, roll-up digital maps, wearable video displays and wireless daily updateable newspapers. As a group, such displays have been referred to as flexible displays. These displays are advertised as thinner (almost paper thin), lighter weight, stronger (extremely rugged and durable), cheaper, super efficient and conformable, as compared to current rigid, mounted displays. When achieved, true flexible displays would have widespread applications in computers, cell phones, advertising displays, maps and even clothing. Military applications could be unending, e.g., adaptable camouflage, wearable computers, transparent windscreen displays and real-time roll-up tactical maps.

Figure 1. Prototype pen with a built-in roll-up display to show off the promise of organic light-emitting diode technology (Source: Universal Display Corporation).

Defining flexible displays

By consensus, the phrase “flexible display” refers to a display that has (or will have) certain physical and operational characteristics that guarantee an unlimited variation of morphology. They will be extremely thin (truly paper-like), extraordinarily lightweight and less bulky, capable of operating over a wide environmental range (e.g., temperature, pressure, and moisture), resistant to vibration and shock, commercially inexpensive (almost throw-away), ultra-conservative in power requirements, capable of supporting video rates, and available in a near infinite combination of form factors and sizes.

Display industry newsletters and product announcements often use the phrase “flexible display technologies.” In actuality, there are no dedicated flexible display technologies. Current and proposed flexible displays merely utilize advanced subclasses of existing display technologies. At the current developmental stage of flexible displays, organic LEDs (OLEDs) and bi-stable electrophoresis are the leading technologies. However, plasma and LCD technologies are also represented.

OLED displays

Generic LEDs have been around for decades, used as digital displays in early calculators and watches, and as indicator lights in electronic instruments. LEDs operate on the principle of semiconductor physics where electrical energy is converted into light energy at a diode junction. Light energy is produced when the junction is forward-biased by an applied voltage. In contrast to conventional LEDs, which act like small lightbulbs, “OLEDs use microscopic polymer materials to generate extremely small light sources that are sandwiched between anode/cathode layers and rest upon thin-film transistors” (Blickenstorfer, 2003). An OLED display is self-emissive, not requiring a backlight. It is characterized by low power consumption, wide operating temperature range, video response rates, full color capability and wide viewing angle (>160 degrees, due to being a Lambertian light source). Current OLEDs have demonstrated limited lifetimes of typically 10,000 hours. OLEDs also have delivered the durability and environmental robustness demanded by occupational applications (Hack et al., 2001).

While standard OLED displays have already found a number of commercial and military applications, advanced OLED displays incorporating flexible metal foils or polymer films are being identified as the leading example of the new flexible class of displays. These newer OLED displays have been referred to as flexible OLEDs or FOLEDs (Figure 2). FOLEDs are touted as being thinner and lighter than current LCDs, consuming less power than LEDs, and being less expensive than either of these technologies. In the future FOLEDs may have large television screen applications as well as potential camouflage benefits for the military (Gardner, 2004). However, to date, FOLEDs have been unable to demonstrate sufficient operating lifetimes or the ability to withstand repetitive flexing.

Figure 2. Prototype FOLED (Flexible Organic Light Emitting Device) technology, using a flexible substrate (Source: Universal Display Corporation).

The next generation OLED device may be the phosphorescent OLED (PHOLED™). PHOLEDs are a proprietary display technology developed by the Universal Display Corporation. Soluble phosphorescent small molecule materials are used to create the OLEDs. PHOLED technology works on the principle that certain organic molecules emit light when an electric current is applied. PHOLED efficiencies are reported to be significantly higher than for conventional OLEDs (Hack et al., 2003).

Two even more exotic types of OLEDs are Transparent OLEDs (TOLEDs) and Stacked OLEDs (SOLEDs). TOLEDs use a proprietary transparent contact to create displays that can be made to be top-only emitting, bottom-only emitting, or both top and bottom emitting (transparent). TOLEDs can greatly improve contrast, making it much easier to view displays in bright sunlight. TOLEDs can be 70% transparent when turned off, making them ideal for integration into car windshields, architectural windows, and eyewear (Universal Display Corporation, 2004a).

SOLEDs uses an array of vertically-stacked TOLED sub-pixels. The stacking of red, green, and blue subpixels on top of one another, instead of next to one another as is commonly done in CRTs and LCDs, improves display resolution up to three-fold and enhances full-color quality. By adjusting the ratio of currents in the three subpixels, color is tuned. By varying the total current through the stack, brightness is varied. By modulating the pulse width, gray scale is achieved. With this SOLED architecture, each pixel can, in principle, provide full color eyewear (Universal Display Corporation, 2004b).

A major issue with all OLED displays is protection against water vapor and oxygen. Such protection requires some form of encapsulation of the OLED material. To provide the advantages of flexibility, classical glass plates must be replaced with conformal materials (e.g., plastics or other flexible materials). Such materials must serve as moisture and oxygen barriers and be transparent. One innovative approach has been to develop Flexible Glass™ using a polymer base such as polyethylene teraphthalate (PET) (Allen, 2003).

Electrophoretic displays

The second leading flexible display technology is electrophoresis. See Figure 3. Electrophoresis is a phenomenon based on the migration of charged particles when placed under the influence of an electrical field. An electrophoretic display would generally consist of a lower electrode (with protection layers), a layer of charged particles within a medium such as a dielectric fluid, and an upper electrode with protection layers.

A novel example of this technology is a product called Radio Paper^{TM} under development by E-Ink (Ritter, 2001; Goldberg, 2003). It is a display that will have the look, feel and bend characteristics of a typical newspaper, with the advanced feature that it can be updated as needed via wireless technology. The main element of Radio Paper^{TM} is an electronic ink, consisting of millions of microcapsules filled with negatively charged black and positively charged white pigments. When a positive charge is applied, the black particles move to the surface, creating black text and images against an otherwise white (negatively charged) background. The microcapsules can retain their charge (and hence the image) for as long as months without additional power.

Figure 3. Example of eltrophoretic display (Source: E-Ink Corporation).

The microcapsules are suspended in a liquid medium, which allows them to be printed onto virtually any flexible substrate, e.g., plastic, glass, fabric, etc. The substrate is then laminated to a layer of circuitry that forms a pixel array controlled by the driver circuitry. The circuitry serves as the display's rear electrode. The second, front, electrode is transparent, allowing viewing of the image formed by the interaction between the microcapsules and the driver circuitry (E-Ink, 2002). See Figure 4.

Besides low power consumption, Radio Paper^{TM} will provide the advantages of higher luminance and contrast as compared to current LCDs, the potential for high resolution (limited only by the size of the microcapsules), and wide viewing angle without loss of luminance and contrast. The major disadvantage is a current update speed of multiple seconds. However, update speeds are expected to be significantly improved by the currently expected low volume availability target date of 2007-2008.

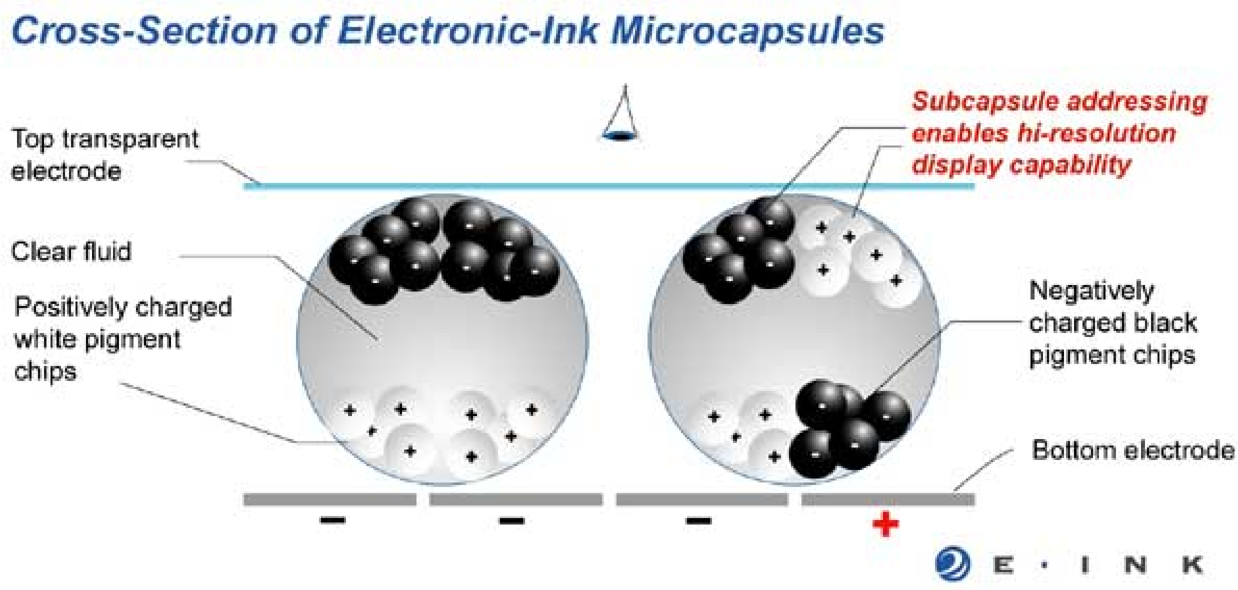

Figure 4. Cross-section diagram of E-Ink based display. (Source: E-Ink Corporation)

Flexible substrate requirements

For all flexible displays, success depends on the development of suitable conformable substrates. The technical design challenges for these substrates are not minimal. These substrates must meet demanding requirements for optical properties, surface quality, dimensional stability, solvent resistance, and oxygen and water transmission (Sarma et al., 2003).

Substrates must have optical properties at least as good as glass, i.e., >85% over the visible spectrum. Surface smoothness is essential to allow applications of display material and barrier coatings. The frequency of surface peaks exceeding 50 nanometers must be minimized. Changes in substrate dimensions due to temperature and pressure variations must be kept to <0.05-0.1% over the application operating temperature range. Substrates must be resistant to most acids and organic solvents. Current barrier goals for protection of OLEDs limit water vapor transmission rates to $<10^{-6}$ gram/m^2/day and oxygen transmission rates to $<10^{-5}$ milliliter/m^2/day (Sarma et al., 2003).

Major flexible display initiatives

Two major initiatives to encourage development within the flexible display technology arena have been recently implemented. The first of these was by the Defense Advanced Research Projects Agency (DARPA) (DARPA, 1999). In January 1999, DARPA issued Broad Agency Announcement 99-17, "Flexible Display Program." Its objective was to stimulate development of flexible displays with increased power efficiency, reduced weight, increased brightness, improved ruggedness, and lower cost. There was an interest in both emissive and transmissive displays. DARPA envisioned that the lighter weight and improved ruggedness of flexible displays would find numerous applications in military vehicles, aircraft, ships, and mobile ground troops. The program was cited as having $30 million in funding and a performance period of three years.

The guidelines of the solicitation were:

> "The flexible display technology developed under this program must not only be rugged and light weight, it must also be compatible with DoD operational environments, temperature (-30 to +85° C), shock, vibration, and humidity environments. The proposed activities should lead to the demonstration of a full color, flexible display capable of full motion video. Suggested performance goals include the following: brightness >150 cd/m^2, resolution $\geq$ 80 lines/inch, a diagonal $\geq$ 15 inches, overall power efficiency > 3 lumens/watt, and a color gamut comparable to cathode ray tube technology. Only proposals that can provide the required demonstration will be considered. While flexibility to improve ruggedness is required, the ability to be able to mold or form the display is a plus, with the long-term goal being to produce roll-up displays. In order to meet the long-term cost goals of the project, it will be necessary to use web-based, roll-to-roll processing in the future. Technology proposed under this program should be compatible with web-based processing, but the demonstration does not need to be accomplished using web-based processing.
>
> In order to achieve the goal of demonstrating a fully functional, flexible display by the end of the program, it is expected that teams will be formed to address the many issues. Tasks which should be addressed in the proposal include, but are not limited to: 1) method of light generation, 2) substrate to be used, 3) amount of flexibility, 4) reliability, 5) expected efficiency, 6) drive electronics, 7) pixel design, and 8) packaging."

DARPA reports on the results of this effort have not yet been completed. However, technical papers at scientific conferences have documented tangible results attributable (wholly or in part) to the DARPA program. These include the first commercial insertion for OLEDs by Pioneer as small passive matrix automobile displays for stereos and cellular phones, as well as basic work in developing organic thin-film transistors (Pellegrino et al., 2003; Tohma, 2000).

The second thrust is the U.S. Army's Flexible Display Initiative (FDI). This initiative is in response to the Army Transformation Program and its recognition of the need for advanced information displays. The FDI has a FY04-FY09 timeframe. The Army FDI is aimed at the development of emissive and reflective flat panel displays on flexible substrates. The future Army's use of sophisticated electronic devices requires displays that can faithfully transmit all the information available. Current display state of the art is flat panel displays manufactured on glass. However, a goal of the FDI is to replace current glass components with plastic substrates and introduce conformal and flexible displays with the additional advantages of lighter weight, ruggedness, low-cost and low power consumption. Flexible displays could be rolled or folded up when not in use. They could be worn and contoured or conformed for the soldier and vehicle platforms. Flexible displays will allow displays to be ubiquitous, offering significantly enhanced capabilities to interface with electronic devices (Pellegrino et al., 2003).

Under the FDI, the Army Research Laboratory has awarded Arizona State University (ASU) a $43.7 million, five-year cooperative agreement to establish the Army Flexible Display Center (FLDC), where flexible, low-power computer displays will be developed that can be continually refreshed with new data and carried in the field, under virtually all weather and environmental conditions. This $43.7 million agreement has a performance period of five years with an option for an additional $50 million over an added five-year period. The ASU FLDC is a university-industry-government collaboration that will provide a national asset in flexible display technology research, development and prototype manufacturing (Gonzales, 2004).

Cockpit applications

The promised characteristics of flexible displays make them highly suitable for use in the aviation cockpit. First, the reduced weight, volume and power consumption, along with improved sunlight readability are all in perfect harmony with the constraints of today's cockpit where weight, space and power are at a premium. Second, the transport nature of TOLEDs may allow designers to develop and implement true "head-up" displays by embedding the displays into the windscreen and/or cockpit windows.

Of perhaps less impact, but certainly welcomed by any pilot or crewman, will be the potential to reduce piles of maps and manuals into a single roll-up pen style display that fits nicely into a pocket but be retrieved as needed. With wireless capability, such an electronic book could be continually and easily updated.

Since as early as 2002, aviation crew station designers have been working on overcoming the technological challenges of OLEDs in producing displays using bendable plastic polymers as substrates. Their expected payoff for aviation could be enormous as panoramic flight displays and ultra-thin, twistable handheld cockpit displays for portraying electronic approach charts, checklists and other flight-related information become part of the avionics suite. (Pope, 2002)

Human factors issues

New display technologies are not immune to good human factors design. In the cockpit, these new displays still will have to meet the human factors requirements for usability. The issues of luminance (brightness) and contrast, luminance uniformity, absence of glare, color rendition and uniformity (as required) must be appropriately addressed for the required tasks. Displays must provide suitable dimming capability to ensure legibility over the full environmental operating range.

Regardless of the display technology employed, users must be able to obtain needed information from displays, readily use switches and controls, consult navigation maps, and perform other required visual tasks, both inside and outside of the cockpit.

Conclusion

The utilization of advanced LED, LCD, electrophoresis and other display technologies to achieve the next holy-grail of displays ---super-thin, conformable and fully bendable displays ---is rapidly coming to fruition. With OLEDs and electrophoretic displays leading the field, flexible displays rolled into pens and twisted into any conceivable shape will soon replace the plasma television as the hot-ticket item in the consumer community. With electronic-paper displays replacing manuals and maps and transparent OLEDs (TOLEDSs) being mapped to windscreens, flexible displays that still meet demanding human factors requirements, have considerable future role in the aviation cockpit.

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